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Contaminant Concentrations are Higher in Farm-raised Salmon as Compared to Wild Salmon

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Abstract

The concentrations of over 30 contaminants were measured in farm-raised and wild salmon. Eighteen composite samples of 180 farm-raised and wild salmon were measured; there were 10 fish per composite. The fish were purchased from commercial distributors in the United States and Canada but included fish farmed or caught in Canada, Chile, Norway, and the United Sates. All measurements were made using gas chromatographic mass spectrometry with isotopic internal standards. On a wet weight basis, the concentrations of polychlorinated biphenyls (PCB), dioxins, almost all pesticides (including toxaphene), polybrominated diphenyl ethers (PBDE, flame retardants), and organic arsenic were significantly higher in the farm-raised fish as compared to their wild colleagues. In fact, the PCB and PBDE concentrations were about nine times higher in the farm-raised fish compared to the wild fish. On a lipid adjusted basis, many of these differences disappeared, but PCBs and PBDEs were still significantly elevated by about a factor of three.

Introduction

The occurrence of persistent and bioaccumulative chemicals in tissues of freshwater and marine organisms is a problem of global significance. In the United States alone, every state, except Colorado and Alaska, has issued advisories against fish consumption from specific bodies of water. In 2000, there were 2,242 such advisories based on mercury, 726 advisories based on PCBs, and lesser numbers based on chlorinated pesticides, dioxins, and DDT.[1, 2]

This problem has been documented most thoroughly in regions such as the Great Lakes, where fish tissue concentrations of PCBs, mercury, and other organic and inorganic compounds have been monitored for more than twenty years.[3, 4, 5] Recently, this problem has become more widely publicized as a result of warnings issued by the U.S. Food and Drug Administration[6] for women and children to reduce or eliminate consumption of commercially sold marine fish including shark, swordfish, mackerel, and tilefish due to mercury contamination.

Salmon, which was not included on the most recent FDA consumption advisory, is a very popular fish for human consumption and is a healthy source of protein and omega-3 polyunsaturated fatty acids.[7, 8] Over the last several years, commercially-sold salmon (salmon purchased in stores and restaurants as opposed to those caught by sport anglers) has become increasingly popular due to its availability and lower price, which are the result of a practice commonly referred to as fish farming or aquaculture. Today, farm-raised salmon comprise the majority of fish consumed in commercial markets. Despite this increasing popularity, however, only minimal attention has been paid to the contaminants in farm-raised vs. wild fish.

In 1994, Pfaffenberger et al. reported that the lipid-adjusted concentrations of the insecticide bromocyclen were not significantly different in Danish farmed rainbow trout (*Oncorhynchus mykiss*) as compared to other species of fish collected in Germany.[9] However, a total of only eight fish were analyzed, and the farmed and wild fish came from different locations. Mayer showed that the lipid-adjusted concentrations of polychlorinated dibenzo-*p*-dioxins and dibenzofurans in "free living trout and carp from rivers and lakes in Bavaria [Germany] were not elevated compared to fishes from farming."[10] In this case, more samples (65) covering two species were analyzed. Urdaneta et al., who analyzed 210 samples of farm-raised fish but no wild fish, found a variety of chlorinated pesticides (including DDT and lindane) in 10 species of farmed fish from three ponds in Venezuela.[11] A similar study by Sahagun et al. found several chlorinated pesticides in farmed rainbow trout taken from four fish farms in Spain,[12, 13] but again there were no wild fish analyzed for comparison. In an interesting study of Egyptian fish, Shereif and Mancy[14] found that organochlorine pesticides and heavy metals were detected at higher levels in fish from Lake Manzala fish farms than in fish reared in treated sewage from the City of Suez. In this case, 12 fish from each of two species were analyzed at each of the two locations.

More recently, studies of polychlorinated dibenzo-*p*-dioxins, dibenzofurans, and biphenyls (PCBs) in 40 farm-raised fish from England and Wales "did not indicate the existence of any health risk from consumption of trout produced in England and Wales."[15] No wild fish were analyzed in this study, so it was not possible to compare these two populations. Similarly, several organochlorine and organophosphate pesticides were generally not detected (with a limit of detection of 10 ng/g) in 290 farm-raised

channel catfish and rainbow trout[16] and metal concentrations "were much lower than recommended safety limits" and lower than reported in wild fish.[17] In contrast, a study of dioxins in the United States' food supply concluded that "the food category with the highest World Health Organization dioxin toxic equivalent concentrations was farm-grown freshwater fish fillet."[18] It is not clear how many fish were analyzed in this last study.

Two recent studies have focused exclusively on farm-raised salmon. Easton et al. examined a limited number of salmon from the Pacific coast (four farm-raised fish and four wild fish) and found consistently higher levels of PCBs, polybrominated diphenyl ethers (PBDEs, used as flame retardants), and organochlorine pesticides (except toxaphene) in the farm-raised fish compared to wild fish.[19] These authors expressed "concern for individuals who on a regular weekly basis consume farmed salmon produced from contaminated food." Studies by Jacobs et al., who analyzed farm-raised salmon (nine fish from Scotland) and reported "relatively high concentrations" of dioxins, support these results. However, there was "no statistically significant difference between the farmed and wild fish."[20]

Clearly the literature is confused on the simple question: Do farm-raised fish (salmon in this case) have higher concentrations of contaminants compared to wild fish? Many of the previous studies suffer from experimental designs that did not sample both farmed and wild fish, from analytical work with poor (that is, inappropriately high) detection limits, or from sampling and analyzing too few fish. In this study, we address this question by analyzing both farm-raised and wild salmon in sufficiently high numbers, and with sufficiently sensitive analytical methods, to determine if the concentrations of

over 30 pollutants were significantly different between farm-raised and wild fish. Answering this question is the first step in determining whether there might be health risks associated with farmed salmon fish.

Methods and Materials

Sampling. All fish were farm-raised or wild salmon. The farm-raised fish (*Salmo salar*) were purchased from commercial suppliers in the United States and Canada and were selected to include salmon farmed or caught in British Columbia, Canada; Chile; Maine, United States; and Norway. Three suppliers provided fish from each region for a total of 12 samples of farm-raised Atlantic salmon. Four other suppliers provided six samples of wild Pacific salmon from Alaska, United States and British Columbia, Canada. The wild fish included three samples of the Chum species (*Oncorhynchus keta*) and three of the Coho species (*Oncorhynchus kistuch*). The guts from all fish were removed before they were shipped, and the heads and gills were left on the fish.

All samples came to the analytical laboratory (Axys Analytical in Sidney, British Columbia) fresh or frozen on ice or gel-packs. The fish were thawed and inspected by a wildlife biologist to verify species. Each fish was weighed, and its length was measured. In each case, ten fish were ground and re-ground together to make a homogenous composite.

Analysis. In general, we used approved US Environmental Protection Agency (EPA) methods. Most of these methods were based on gas chromatographic high resolution mass spectrometry (GC/HRMS) with isotopically labeled internal standards.

Chlorinated dibenzo-*p*-dioxins and dibenzofurans were measured using EPA Method 1613, which was calibrated with an extra standard that was 5 times lower in concentration than the method requirement. This precaution, along with suitably clean procedural blanks, allowed us to report data with a detection limit 5 times lower than the method specification. Twenty-five grams of wet fish tissue were mixed with ^{13}C-labeled internal standards (15 individual compounds), ground with anhydrous sodium sulfate, and Soxhlet extracted with 1:1 dichloromethane:toluene for 16 hours. The extract was cleaned up by gel permeation chromatography on Biobeads SX-3 and fractionated on Florisil, silica, alumina, and carbon. The analysis was performed on a Micromass Autospec Ultima magnetic sector mass spectrometer equipped with a Hewlett Packard 6890 gas chromatograph. The instrument was operated at a static mass resolution of 10,000. Chromatographic separation was achieved using a Durabond DB-5 column (60-m × 250-μm i.d., 0.10-μm film thickness). Second column confirmations were made using a DB-225 column (30-m × 250-μm i.d., 0.15-μm film thickness). The dioxin concentrations are reported as toxic equivalents (TEQs) assuming non-detects are zero and using NATO toxic equivalent factors.

PCBs were quantitated using EPA Method 1668A; this technique is an isotope-dilution, congener-specific method that gives excellent analyte identification and detection limits. Total PCBs were determined by summing the concentration of each individual PCB congener. Ten grams of wet fish tissue were mixed with ^{13}C-labeled internal standards (27 individual PCB congeners), ground with anhydrous sodium sulfate, and Soxhlet extracted with dichloromethane for 16 hours. The extract was cleaned up by gel permeation chromatography on Biobeads SX-3 and fractionated on Florisil, silica, and

alumina. The same GC/HRMS system was used for PCBs as for dioxins. Chromatographic separation was achieved using a Supleco SPB-Octyl column (30-m × 250-μm i.d., 0.25-μm film thickness).

The organochlorine pesticides were measured using a GC/HRMS isotope dilution method analogous to the EPA methods used for dioxin/furan and PCB analyses. Ten grams of wet fish tissue were mixed with labeled internal standards (eleven ^{13}C-labeled pesticides and two ^{2}H-labeled pesticides), ground with anhydrous sodium sulfate, and Soxhlet extracted with dichloromethane for 16 hours. The extract was cleaned up by gel permeation chromatography on Biobeads SX-3 and fractionated on Florisil. Two fractions were collected (**F1**, the non-polar and medium polarity pesticides, and **F2**, the polar pesticides) and each fraction was analyzed separately. The analyses were performed using a VG 70 VSE magnetic sector mass spectrometer equipped with a Hewlett Packard 5890 gas chromatograph and operated at a static mass resolution of 8,000. Chromatographic separation was achieved using a Durabond DB-5 column (60-m × 250-μm i.d., 0.10-μm film thickness).

The **F1** pesticide fraction was also analyzed for toxaphene by gas chromatographic mass spectrometry operated in the electron capture negative ion (ECNI) mode. This technique is both sensitive and selective for chlorinated bornanes, which are the major constituents of toxaphene. A Micromass Autospec Ultima magnetic sector mass spectrometer equipped with a Hewlett Packard 5890 gas chromatograph and operated at a static mass resolution of approximately 5,000 was used. Chromatographic separation was achieved using a Durabond DB-5 column (60-m × 250-μm i.d., 0.25-μm film thickness). Quantification of individual chlorobornanes (which were summed to produce a to-

tal toxaphene mass) was achieved using PCB 180 (2,2',3',4,4',5,5'-hepta-chlorobiphenyl) as the internal standard.

Polybrominated diphenyl ethers (PBDE) were analyzed in the extract prepared for the PCB analysis. Nine individual ^{13}C-labeled brominated diphenylethers were added to the wet fish tissue before extraction for PCBs. GC/MS analysis of PBDEs was accomplished using a VG 70 VSE magnetic sector mass spectrometer equipped with a Hewlett Packard 5890 gas chromatograph operated at a static mass resolution of approximately 5,000. Chromatographic separation was achieved using a Durabond DB-5HT high temperature column (30-m × 250-μm i.d., 0.10-μm film thickness). The PBDE results were obtained by isotope dilution quantification using the ^{13}C-labeled internal standards.

PAH were measured by a gas chromatographic low resolution (quadrupole) mass spectrometric method using deuterium (^{2}H) labeled internal standards. Ten grams of wet tissue were mixed with 14 individual ^{2}H-labeled PAH and digested in methanolic KOH for 3 hours. The digestate was extracted with pentane, and the extract was fractionated on silica. The PAH were analyzed on a Finnigan Incos 50 quadrupole mass spectrometer equipped with a Varian 3400 gas chromatograph. The instrument was operated in the multiple ion detection (MID) mode at unit mass resolution in the electron ionization (EI) mode, and chromatographic separation was achieved using a Restek Rt_x-5 column (30-m × 250-μm i.d., 0.25-μm film thickness). Results were quantified by isotope dilution against the ^{2}H-labeled internal standards.

Lipids were measured gravimetrically after extraction of the fish tissue with 50% dichloromethane in hexane. Each sample was measured in duplicate.

To measure total arsenic, about 0.5 g of the fish tissue were digested in 10-mL of concentrated nitric acid for 5 hours and diluted to 40 mL with reagent water. Arsenic was quantitated by argon inductively coupled plasma mass spectrometry on a Perkin-Elmer ELAN 6000 instrument. Indium was used as the internal standard. The arsenic ion at m/z 75 was corrected for a small interference from the plasma due to ArCl. Total inorganic arsenic was measured using hydride generation, cryogenic trapping, gas chromatography, atomic absorption spectrometry at a sample pH < 2.

To measure mercury, about 0.5 g of the fish tissue was digested in 10-mL of 25% KOH/methanol for 2 hours at 60 °C and diluted to 40 ml with methanol. This digestate was used to measure methyl mercury. For total mercury, a 10-mL aliquot of the original digestate was diluted with 30 mL of 50% 0.2 N BrCl; this oxidizes all of the mercury to Hg^{++}. Mercury was measured by cold-vapor, atomic fluorescence spectrometry. Calibrations were based on NIST certified mercury standards. Measurements for total mercury and methyl mercury gave similar results for each sample; thus, these measurements were considered duplicate measurements and were averaged. The mercury and arsenic measurements were done at Frontier Geosciences in Seattle, Washington.

QA/QC. All analyses were conducted in accordance with Axys' accredited QA/QC program.[21] Each analysis batch of up to 20 samples also included a procedural blank, a "known" or laboratory control sample, and an analysis duplicate. The sample results were reviewed and evaluated in relation to the QA/QC samples worked up at the same time. The sample internal standard recoveries and detection limits, procedural blank data, and laboratory control sample data were evaluated against method criteria to ensure data

quality. All instrument QA specifications of EPA Methods 1613 and 1668 were adhered to and applied to all analyses conducted for this study.

Results and Discussion

The measured concentrations are presented in Table 1 in picograms of contaminant per gram wet weight of whole fish (pg/g wet) except for those concentrations indicated by an asterisk (*), which are in nanograms per gram wet weight (ng/g wet). In Table 1, the concentrations are reported with two significant figures because we judged the general accuracy and precision of the measurement to be about ± 10%. The calculations of the averages, standard errors, and *t*-values used these rounded data, but these results are reported with three significant figures. Duplicate measurements were averaged before entry in the table.

The QA/QC results were good. In general, duplicate measurements differed from each other by less than 15%. Almost all blank measurements were below the detection limits; hence, blank values were never subtracted from the sample measurements. Some compounds were part of our original analyte list, but they were found so infrequently that they are omitted from Table 1. These include aldrin, endrin aldehyde, heptachlor, 2,4'-DDE, α- and β-endosulfan, and all polycyclic aromatic hydrocarbons except fluoranthene and pyrene. Decabromodiphenyl ether was the only analyte omitted because of a high blank.

As a check on the quality of the data, selected ratios were calculated, and these are given in three rows of Table 1 with italic font. Given the production history of HCH, one would expect that the ratio of the γ- and α-isomers would be about 0.14-0.25,[22] and with a

few exceptions, this was observed. The ratio of DDE to DDT will vary depending on the age of the DDT, a higher ratio indicating an older mixture. Our 4,4'-DDE/4,4'-DDT ratios are 8.1 in the farmed fish and 9.7 in the wild fish. These values are not significantly different ($t = -1.06$, $DF = 8$, $p = 0.32$) and are about what would be currently expected.[23] The two polycyclic aromatic hydrocarbons, fluoranthene and pyrene, are almost always found together at a ratio of about 2:1.[24] Our measured ratio is 2.6 in the farmed fish and 1.6 in the wild. Although these values are significantly different ($t = -3.00$, $DF = 15$, $p < 0.01$), they are similar to what might be expected from normal combustion sources. Taken together, all of these ratios indicated that these data are of high quality.

It was not our purpose to isolate variations among suppliers or geographical regions. Hence, we have treated the twelve samples of farmed salmon as replicates and the six samples of wild salmon as replicates. Remembering that each measured sample was the composite of 10 individual fish, we note that we have analyzed a total of 180 fish. The averages and standard errors of the replicate measurements are given in Table 1 and compared using the Student's t-test (see the rightmost column). All t-values that are significant at the 0.05 level (i.e., $p < 0.05$) are underscored in Table 1; all t-values that are significant at the 0.01 level (i.e., $p < 0.01$) are underscored and in bold font. The critical values for these t-statistics vary with the appropriate degrees of freedom specified by the Welch modified two-sample t-test for unequal variances.[25]

Of the contaminants we measured, total PCB (ΣPCB), dioxins (expressed as toxic equivalents), γ-HCH (also called lindane), heptachlor epoxide (an environmental degradation product of the insecticide heptachlor), dieldrin, endrin ketone (an environmental degradation product of endrin), most of the DDT-related compounds, endosulfan sulfate (an

environmental degradation product of endosulfan), methoxychlor, and all of the brominated diphenyl ethers are more concentrated (at the $\alpha = 0.01$ significance level) in the farm-raised than in the wild salmon. Virtually all of the other organochlorine pesticides (excepting HCB, β-HCH, and 2,4'-DDT) are higher (at the $\alpha = 0.05$ significance level) in the farm-raised salmon than in the wild salmon. Of these pesticides, ΣDDT and toxaphene are especially high in the farm-raised fish, averaging 13 ng/g wet weight and 49 ng/g wet weight, respectively. Total arsenic concentrations in the farm-raised fish are also higher (at the $\alpha = 0.05$ significance level) than in the wild fish. Inorganic arsenic was not detectable (with a limit of detection of 4 ng/g wet weight) in these samples, implying that arsenic was present in the relatively non-toxic organic form. Interestingly, the only substance that is higher in the wild salmon vs. the farm-raised is mercury, but the difference is not statistically significant.

In some cases, the difference between farm-raised and wild salmon is striking. For example, ΣPCB concentrations are 8.8 times as high in the farm-raised as in the wild salmon; the brominated diphenyl ether concentrations (see Σ 5 PBDE) are 9.7 times as high in the farm-raised as in the wild fish; and methoxychlor was never detected in the wild fish, but it was always present in their farm-raised counterparts, although at low levels.

The concentrations in Table 1 are given relative to the wet weight of the homogenized whole fish. It is also common to express such concentrations in terms of the lipid content of the fish. Thus, we measured the lipid fraction of the samples and normalized the concentrations to this fraction. Table 2 gives the concentrations of the various contaminants in units of nanograms per gram lipid, except for the dioxins, which are given in pg TEQ per gram lipid. In Table 2, the concentrations are reported with two significant fig-

ures; the calculations of averages, standard error, and *t*-values used these rounded data, but these results are reported with three significant figures. The *t*-values are coded for significance in the same manner as in Table 1.

The largest difference in Table 2 is the difference in lipid content: 20% in the farm-raised fish vs. 6.8% in the wild fish, which gives a very high *t*-value of 13.3. After lipid normalization, many, but not all, of the differences shown in Table 1 disappear. Almost all of the pesticides from HCB to toxaphene are not significantly different in the farm-raised versus wild salmon. This observation suggests that these compounds are present in the lipids of the fish. The exceptions to this observation are HCB, β-HCH, ΣHCH, and 2,4'-DDT, which have significantly lower lipid-adjusted concentrations in the farmed fish, and endrin ketone, 4,4'-DDD, 4,4'-DDT, endosulfan sulfate, and methoxychlor, which are significantly more concentrated in the farmed fish. Some of the industrial substances remain elevated in the farmed fish even after lipid adjustment. ΣPCB, dioxins, and all of the brominated diphenyl ethers (and of course, ΣPBDE) are still elevated by factors of three. The observation that the pesticides seem to be almost exclusively lipid related but that the industrial chemicals (PCBs, dioxins, and PBDEs) are not is interesting and may indicate different sources of these two groups of chemicals, differential metabolism, or differential chemical partitioning within the fish. Finally, the lipid adjusted mercury and arsenic concentrations are significantly lower in the farm-raised salmon vs. the wild.

The reasons for these large differences between the farm-raised and wild salmon pollutant concentrations are not immediately clear. The farm-raised salmon are significantly bigger ($t = 5.12$), heavier ($t = 6.61$), and fatter ($t = 13.3$) presumably because they get little exercise in the pens in which they are cultivated. The farm-raised salmon are also fed

a carefully formulated diet, which is obtained from forage fish harvested globally. It is not known if the farm-raised fish are younger than their wild counterparts, but given the farming practices involved, it seem likely that they are. Thus, the higher concentrations of the pollutants in the farm-raised salmon may be due to some combination of higher dietary inputs and reduced metabolism or excretion related to the sedentary lifestyle of these fish.

This paper addresses whole salmon homogenates, which people do not eat. The intent of this study was to determine if there were sufficient grounds for the pursuit of a more elaborate study of salmon fillets. It seems clear, especially from Table 1, that farm-raised salmon have much higher concentrations of several pollutants than wild salmon. In some cases, such as PCBs and PBDEs, these differences are very high. Clearly, a more complete study of salmon fillets is desirable and is needed before a useful health risk assessment is possible.

In the next phase of our study, we will sample a much larger number of fish from many more regions throughout the world. The results of this future work will allow us to assess the health risks of consuming farm-raised vs. wild salmon; provide further insight into the wet-weight and lipid adjusted results observed here; and determine the global distribution of contaminants in farm-raised salmon, which are becoming the fish of choice for consumers throughout the world.

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Table 1. Wet Weight Concentrations, in pg/g except those Marked with *, which are in ng/g Wet Weight, of Various Contaminants in Farm-raised and Wild Salmon[a]

	Farmed														Wild								
Supplier	A	B	C	D	B	C	B	C	E	B	C	F		Std.	G	G	H	I	J	I		Std.	
Location	B.C.	B.C.	B.C.	Chile	Chile	Chile	Maine	Maine	Maine	Norway	Norway	Norway	Avg.	Error	Alaska	Alaska	Alaska	B.C.	B.C.	B.C.	Avg.	Error	t-test[b]
Species															Chum	Coho	Coho	Chum	Chum	Coho			
Length (cm)	77	73	77	77	83	79	79	79	73	82	79	82	78.3	0.9	65	68	73	70	74	70	70.0	1.3	**5.12**
Std dev	3	5	2	7	2	1	2	2	3	2	3	2			7	7	2	12	6	3			
Weight (g)	4800	3900	5100	5800	6600	5100	4900	5400	4700	6200	5100	6300	5330	224	2300	3300	3300	3400	4000	3000	3220	227	**6.61**
Std dev	290	820	260	210	270	270	330	370	200	270	390	260			1100	1100	340	630	970	360			
ΣPCB[c]	29*	41*	46*	5*	12*	45*	34*	25*	37*	43*	29*	48*	32.8*	3.9*	3.3*	3.5*	3.9*	3.1*	3.2*	5.4*	3.73*	0.35*	**7.37**
Dioxin TEQ	0.09	0.13	0.32	0.04	0.03	0.52	0.17	0.15	0.22	0.50	0.15	0.45	0.23	0.05	0.03	0.01	0.02	0.03	0.03	0.05	0.0280	0.0054	**3.99**
HCB	1200	1300	1500	820	770	1200	1300	1500	1400	3300	1200	3700	1600	266	1100	1500	1200	940	980	1300	1170	86	1.54
α-HCH	3200	3300	3400	51	57	2700	4200	3200	4200	1000	3100	970	2450	436	1400	2000	1000	770	1300	890	1230	183	2.58
β-HCH	1800	230	1700	21	41	1700	330	1400	270	360	1700	340	824	217	560	720	470	390	620	400	527	53	1.33
γ-HCH	570	440	640	21	24	530	540	590	510	1100	650	1200	568	100	250	330	170	140	230	140	210	30	**3.43**
ΣHCH	5600	4000	5700	93	120	4900	5100	5200	5000	2500	5500	2500	3840	595	2200	3100	1600	1300	2200	1400	1970	276	2.87
γ/α HCH	*0.18*	*0.13*	*0.19*	*0.41*	*0.42*	*0.20*	*0.13*	*0.18*	*0.12*	*1.1*	*0.21*	*1.2*	*0.39*	*0.11*	*0.18*	*0.17*	*0.17*	*0.18*	*0.18*	*0.16*	*0.1720*	*0.0038*	1.84
Oxychlor	110	430	240	51	45	220	360	280	460	730	120	730	315	68	120	170	170	110	110	150	138	12	2.54
Hep epox	120	240	310	43	<2.3	220	180	160	240	440	140	470	214	41	64	120	60.	59	60.	79	73.7	9.8	**3.33**
α-Chlor	450	1100	1600	170	190	1300	1200	1200	1400	3500	520	3800	1370	337	430	620	610	400	430	660	525	48	2.48
γ-Chlor	110	130	330	42	38	330	180	210	200	640	160	680	254	61	89	120	120	93	110	120	109	5.8	2.38
***cis*-Nona**	120	660	610	37	37	640	570	490	710	1300	220	1700	591	144	160	220	170	120	120	220	168	18	2.91
***trans*-Nona**	390	1900	1600	100	97	1300	1700	1200	2100	3300	530	3600	1480	331	520	660	590	440	380	600	532	43	2.86
Dieldrin	620	1200	1400	300	320	1200	1300	890	1700	2800	670	2900	1280	246	220	400	260	210	210	300	267	30	**4.07**
Endrin	140	130	170	45	58	160	180	180	230	530	96	510	202	45	66	130	79	56	85	91	84.5	10.5	2.53
End Keto	9	11	17	6	5	13	12	13	11	23	7	37	13.7	2.6	<3.2	7	<3.9	<3.8	<3.3	<4.1	1.17	1.17	**4.45**
ΣChlor	2100	5800	6300	790	790	5400	5700	4600	7100	13000	2500	14000	5670	1220	1700	2400	2100	1500	1500	2200	1900.	157	3.06
2,4'-DDD	260	150	650	67	79	530	250	240	220	440	250	600	311	57	98	99	73	100	94	85	91.5	4.3	**3.86**
4,4'-DDD	1800	1500	4800	360	510	4300	1800	1600	1800	2700	1800	3500	2210	397	240	300	360	270	280	420	312	27	**4.76**
4,4'-DDE	7.5*	7.5*	24*	1.5*	2.4*	18*	9.4*	6.7*	7.5*	10.*	7.4*	11*	9.41*	1.79*	0.98*	1.5*	2.1*	1.5*	1.9*	2.9*	1.81*	0.27*	**4.19**
2,4'-DDT	210	220	410	70	110	320	270	300	280	960	230	1100	373	93	280	270	230	210	160	340	248	25	1.30
4,4'-DDT	680	860	2000	290	460	1900	1200	800	780	1900	740	2200	1150	193	210	190	160	160	180	230	188	11	**4.99**
ΣDDT	11*	10.*	32*	2.3*	3.6*	25*	13*	9.6*	11*	16*	10.*	18*	13.5*	2.4*	1.8*	2.4*	2.9*	2.2*	2.6*	4.0*	2.65*	0.31*	**4.42**
DDE/DDT[d]	*11*	*8.7*	*12*	*5.2*	*5.2*	*9.5*	*7.8*	*8.4*	*9.6*	*5.3*	*10.*	*5.0*	*8.14*	*0.71*	*4.7*	*7.9*	*13*	*9.4*	*11*	*12*	*9.70*	*1.29*	*-1.06*

	Farmed														Wild								
Supplier	A	B	C	D	B	C	B	C	E	B	C	F		Std.	G	G	H	I	J	I		Std.	
Location	B.C.	B.C.	B.C.	Chile	Chile	Chile	Maine	Maine	Maine	Norway	Norway	Norway	Avg.	Error	Alaska	Alaska	Alaska	B.C.	B.C.	B.C.	Avg.	Error	*t*-test
Species															Chum	Coho	Coho	Chum	Chum	Coho			
Mirex	15	30	42	63	17	35	36	23	43	63	16	81	38.7	6.1	17	27	24	14	10.	33	20.8	3.5	2.53
Endo sulf	200	190	330	140	150	160	140	67	170	400	150	380	206	30	16	17	9	26	22	24	19.0	2.6	**6.16**
Methoxy	25	8	9	3	12	7	14	10.	10.	21	7	13	11.6	1.8	<2.3	<2.4	<2.4	<1.8	<2.4	<1.8	0	0	**6.52**
ΣPest	20*	22*	46*	4.2*	5.4*	37*	25*	21*	24*	36*	20*	40*	25.1*	3.7*	6.8*	9.4*	7.9*	6.0*	7.3*	9.0*	7.73*	0.53*	**4.61**
Toxaphene	21*	44*	29*	15*	8.4*	32*	33*	63*	52*	82*	30*	180*	49.1*	13.3*	6.1*	15*	9.0*	3.1*	41*	14*	14.7*	5.6*	2.39
Fluoran	1500	1100	450	440	620	890	390	180	670	1000	3000	810	921	216	440	330	250	850	430	670	495	92	1.82
Pyrene	460	370	200	240	250	340	180	220	330	310	730	270	325	43	320	250	110	550	370	310	318	59	0.09
Fluor/pyrene	*3.3*	*3.0*	*2.3*	*1.8*	*2.5*	*2.6*	*2.2*	*0.82*	*2.0*	*3.2*	*4.1*	*3.0*	*2.56*	*0.24*	*1.4*	*1.3*	*2.3*	*1.5*	*1.2*	*2.2*	*1.64*	*0.19*	**3.00**
BDE-47	560	1400	2200	180	190	2000	1700	560	1500	1300	1000	1500	1170	195	48	60	100	94	130	230	110	27	**5.40**
BDE-99	200	330	400	67	99	330	390	140	390	370	270	400	282	36	23	19	41	47	76	50	42.7	8.4	**6.49**
BDE-100	100	270	460	32	37	400	340	98	310	220	160	250	223	41	8	10.	18	16	29	38	29.8	4.7	**4.97**
BDE-153	17	67	66	7	9	60.	61	18	47	58	23	61	41.2	7.0	3	2	5	8	7	5	5.00	0.93	**5.15**
BDE-154	28	100	120	14	14	110	97	35	89	110	40	120	73.1	12.4	4	4	7	7	10.	9	6.83	1.01	**5.33**
Σ 5 PBDE	910	2200	3300	300	350	2900	2600	850	2300	2100	1500	2300	1800	289	86	95	170	170	250	330	184	38	**5.56**
Mercury	16*	13*	15*	16*	19*	12*	15*	18*	38*	25*	14*	24*	18.8*	2.1*	30*	21*	27*	21*	17*	27*	23.8*	2.0*	−1.75
Arsenic	500*	390*	490*	330*	510*	450*	480*	380*	1100*	1400*	510*	1400*	662*	114*	410*	490*	380*	290*	300*	380*	375*	30*	2.42

a. Non-detects are given as less than the detection limit (for example < 2.3 ng/g wet), but the statistical calculations used zero for these values.

b. The *t*-test values are given in bold and underscored if the difference between the farm-raised and wild fish concentrations is significant with >99% confidence and underscored only if the difference is significant with 95-99% confidence.

c. Abbreviations: PCB, polychlorinated biphenyl; HCB, hexachlorobenzene; HCH, hexachlorocyclohexane; oxychlor, oxychlordane; hep epox, heptachlor epoxide; chlor, chlordane; nona, nonachlor; end keto, endrin ketone; endo sulf, endosulfan sulfate; methoxy, methoxychlor; pest, pesticides; fluoran, fluoranthene; and BDE, brominated diphenyl ether.

d. 4,4'-isomers only, correcting units to obtain a dimensionless ratio

* ng/g wet weight

Table 2. Lipid Adjusted Concentrations, in ng/g Lipid except for Dioxins, which are in pg TEQ/g Lipid, of Various Contaminants in Farm-raised and Wild Salmon.[a]

	Farmed														Wild								
Supplier	A	B	C	D	B	C	B	C	E	B	C	F		Std.	G	G	H	I	J	I		Std.	
Location	B.C.	B.C.	B.C.	Chile	Chile	Chile	Maine	Maine	Maine	Norway	Norway	Norway	Avg.	Error	Alaska	Alaska	Alaska	B.C.	B.C.	B.C.	Avg.	Error	*t*-test
Species															Chum	Coho	Coho	Chum	Chum	Coho			
Lipid %	17.5	15.5	22.7	17.3	21.4	19.8	19.9	18.4	20.7	23.2	20.0	25.0	20.1	0.8	7.4	9.3	5.3	5.3	7.3	6.2	6.80	0.63	**13.3**
ΣPCB	170	260	200	29	56	230	170	140	180	190	150	190	165	19	45	38	74	58	44	87	57.7	7.9	**5.13**
Dioxin	0.51*	0.84*	1.4*	0.23*	0.14*	2.6*	0.85*	0.82*	1.1*	2.2*	0.75*	1.8*	1.10*	0.22*	0.41*	0.11*	0.38*	0.57*	0.41*	0.81*	0.45*	0.09*	2.73
HCB	6.9	8.4	6.6	4.7	3.6	6.1	6.5	8.2	6.8	14	6.0	15	7.73	0.99	15	16	23	18	13	21	17.7	1.5	**-5.42**
α-HCH	18	21	15	0.29	0.27	14	21	17	20	4.3	16	3.9	12.6	2.3	19	22	19	15	18	14	17.8	1.2	-2.02
β-HCH	10.	1.5	7.5	0.12	0.19	8.6	1.7	7.6	1.3	1.6	8.5	1.4	4.17	1.11	7.6	7.7	8.9	7.4	8.5	6.5	7.77	0.35	**-3.09**
γ-HCH	3.3	2.8	2.8	0.12	0.11	2.7	2.7	3.2	2.5	4.7	3.3	4.8	2.75	0.42	3.4	3.5	3.2	2.6	3.2	2.3	3.03	0.19	-0.61
ΣHCH	32	26	25	0.54	0.57	25	25	28	24	11	27	10.	19.6	3.2	30	33	31	25	29	23	28.5	1.5	**-2.52**
Oxychlor	0.63	2.8	1.1	0.29	0.21	1.1	1.8	1.5	2.2	3.1	0.60	2.9	1.53	0.30	1.6	1.8	3.2	2.1	1.5	2.4	2.10	0.26	-1.44
Hep epox	0.69	1.5	1.4	0.25	<0.01	1.1	0.90	0.87	1.2	1.9	0.70	1.9	1.03	0.17	0.86	1.3	1.1	1.1	0.82	1.3	1.08	0.08	-0.24
α-Chlor	2.6	7.1	7.0	0.98	0.89	6.6	6.0	6.5	6.8	15	2.6	15	6.42	1.34	5.8	6.7	12	7.5	5.9	11	8.15	1.10	-1.00
γ-Chlor	0.63	0.84	1.5	0.24	0.18	1.7	0.90	1.1	0.97	2.8	0.80	2.7	1.20	0.24	1.2	1.3	2.3	1.8	1.5	1.9	1.67	0.17	-1.58
***cis*-Nona**	0.69	4.3	2.7	0.21	0.17	3.2	2.9	2.7	3.4	5.6	1.1	6.8	2.81	0.60	2.2	2.4	3.2	2.3	1.6	3.6	2.55	0.30	0.39
***trans*-Nona**	2.2	12	7.0	0.58	0.45	6.6	8.5	6.5	10.	14	2.7	14	7.04	1.40	7.0	7.1	11	8.3	5.2	9.7	8.05	0.85	-0.61
Dieldrin	3.5	7.7	6.2	1.7	1.5	6.1	6.5	4.8	8.2	12	3.4	12	6.13	1.00	3.0	4.3	4.9	4.0	2.9	4.8	3.98	0.35	2.02
Endrin	0.80	0.84	0.75	0.26	0.27	0.81	0.90	0.98	1.1	2.3	0.48	2.0	0.96	0.18	0.89	1.4	1.5	1.1	1.2	1.5	1.27	0.10	-1.50
End Keto	0.05	0.07	0.07	0.03	0.02	0.07	0.06	0.07	0.05	0.10	0.04	0.15	0.065	0.010	<0.04	0.08	<0.07	<0.07	<0.06	<0.07	0.013	0.013	**3.11**
ΣChlor	12	37	28	4.6	3.7	27	29	25	34	57	12	58	27.4	5.2	23	26	39	28	21	36	28.8	2.9	-0.23
2,4'-DDD	1.5	0.97	2.9	0.39	0.37	2.7	1.3	1.3	1.1	1.9	1.3	2.4	1.51	0.24	1.3	1.1	1.4	1.9	1.3	1.4	1.40	0.11	0.43
4,4'-DDD	10.	9.7	21	2.1	2.4	22	9.0	8.7	8.7	12	9.0	14	10.7	1.8	3.2	3.2	6.8	5.1	3.8	6.8	4.82	0.69	**3.14**
4,4'-DDE	43	48	110	8.7	11	91	47	36	36	43	37	44	46.2	8.3	13	16	40	28	26	47	28.3	5.4	1.81
2,4'-DDT	1.2	1.4	1.8	0.40	0.51	1.6	1.4	1.6	1.4	4.1	1.2	4.4	1.75	0.36	3.8	2.9	4.3	4.0	2.2	5.5	3.78	0.47	**-3.45**
4,4'-DDT	3.9	5.5	8.8	1.7	2.1	9.6	6.0	4.3	3.8	8.2	3.7	8.8	5.53	0.79	2.8	2.0	3.0	3.0	2.5	3.7	2.83	0.23	**3.28**
ΣDDT	60	66	140	13	17	130	65	52	51	69	52	74	65.8	10.8	24	25	55	42	36	64	41.0	6.6	1.95
Mirex	0.09	0.19	0.19	0.36	0.08	0.18	0.18	0.13	0.21	0.27	0.08	0.32	0.19	0.03	0.23	0.29	0.45	0.26	0.14	0.53	0.32	0.06	-1.95
Endo sulf	1.1	1.2	1.5	0.81	0.70	0.81	0.70	0.36	0.82	1.7	0.75	1.5	0.99	0.11	0.22	0.18	0.17	0.49	0.30	0.39	0.29	0.05	**5.57**
Methoxy	0.14	0.05	0.04	0.02	0.06	0.04	0.07	0.05	0.05	0.09	0.04	0.05	0.058	0.009	<0.03	<0.03	<0.05	<0.03	<0.03	<0.03	0	0	**6.52**
ΣPest	110	140	200	24	25	190	130	110	120	150	99	160	122	16	92	100	150	110	100	150	117	10.	0.24
Toxaphene	120	280	130	87	39	160	170	340	250	350	150	720	233	52	82	160	170	58	560	230	210.	75	0.25

	Farmed														Wild								
Supplier	**A**	**B**	**C**	**D**	**B**	**C**	**B**	**C**	**E**	**B**	**C**	**F**		**Std.**	**G**	**G**	**H**	**I**	**J**	**I**		**Std.**	
Location	**B.C.**	**B.C.**	**B.C.**	**Chile**	**Chile**	**Chile**	**Maine**	**Maine**	**Maine**	**Norway**	**Norway**	**Norway**	**Avg.**	**Error**	**Alaska**	**Alaska**	**Alaska**	**B.C.**	**B.C.**	**B.C.**	**Avg.**	**Error**	***t*-test**
Species															**Chum**	**Coho**	**Coho**	**Chum**	**Chum**	**Coho**			
Fluoran	8.6	7.1	2.0	2.5	2.9	4.5	2.0	0.98	3.2	4.3	15	3.2	4.69	1.13	6.0	3.6	4.7	16	5.9	11	7.87	1.93	-1.42
Pyrene	2.6	2.4	0.88	1.4	1.2	1.7	0.90	1.2	1.6	1.3	3.7	1.1	1.67	0.24	4.3	2.7	2.1	10.	5.1	5.0	4.87	1.14	-2.74
BDE-47	3.2	9.0	9.7	1.0	0.89	10.	8.5	3.0	7.2	5.6	5.0	6.0	5.76	0.93	0.65	0.65	1.9	1.8	1.8	3.7	1.75	0.46	**3.86**
BDE-99	1.1	2.1	1.8	0.39	0.46	1.7	2.0	0.76	1.9	1.6	1.4	1.6	1.40	0.17	0.31	0.20	0.77	0.89	1.0	0.81	0.66	0.13	**3.40**
BDE-100	0.57	1.7	2.0	0.18	0.17	2.0	1.7	0.53	1.5	0.95	0.80	1.0	1.09	0.19	0.11	0.11	0.34	0.30	0.40	0.61	0.31	0.08	**3.74**
BDE-153	0.10	0.43	0.29	0.04	0.04	0.30	0.31	0.10	0.23	0.25	0.12	0.24	0.20	0.04	0.04	0.02	0.09	0.15	0.10	0.08	0.080	0.019	3.10
BDE-154	0.16	0.65	0.53	0.08	0.07	0.56	0.49	0.19	0.43	0.47	0.20	0.48	0.36	0.06	0.05	0.04	0.13	0.13	0.14	0.15	0.107	0.020	**4.06**
Σ 5 PBDE	5.2	14	14	1.7	1.6	15	13	4.6	11	8.9	7.5	9.3	8.82	1.38	1.2	1.0	3.2	3.2	3.5	5.4	2.92	0.67	**3.86**
Mercury	91	84	66	92	89	61	75	98	180	110	70	96	92.7	9.0	410	230	510	400	230	440	370	47	**-5.80**
Arsenic	2900	2500	2200	1900	2400	2300	2400	2100	5300	6000	2600	5600	3180	435	5500	5300	7200	5500	4100	6100	5620	415	**-4.05**

a. See footnotes in Table 1 for the code for the *t*-values and for the abbreviations

* pg TEQ/g lipid

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